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TRACKING THE MIGRATION OF THE MONARCH BUTTERFLIES WITH THE WORLD'S SMALLEST COMPUTER

Excerpted from "mSAIL: milligram-scale multi-modal sensor platform for monarch butterfly migration tracking" from MobiCom '21: *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking* with permission. https://dl.acm.org/doi/10.1145/3447993.3483263 ©ACM 2021

Each fall, millions of monarch butterflies across the U.S. and Canada migrate up to 4,000 km to overwinter in the same cluster of mountaintops in central Mexico. In spring, these migrants mate and remigrate northwards to repopulate their northern breeding territory over 2–4 partially overlapping generations. Because each migrant monarch completes only part of this round trip and does not return to the overwintering site, this navigational task cannot be learned from the prior generation. The number of monarchs completing the journey has dramatically declined in the past decades, coincident with the decreased availability of their milkweed host plant. The U.S., Mexico, and Canada have invested tremendous resources into monarch conservation efforts, including enacting specific policy initiatives, public outreach programs, and habitat protection and restoration projects. The US invested over $11 million between 2015–2017 alone [1]. Developing a tracking technology for monarch can be a key in these efforts, providing, for instance, detailed understanding of habitat use during migratory flight and dependence on weather conditions. Furthermore, it can significantly benefit animal research, and agricultural and environmental science.

Photo, istockphoto.com

A monarch tracker must assure daily localization of the butterfly as it progresses on its journey while not interfering with its flight. As such, any deployed sensor must perform this task while having a weight in the tens of milligram (mg) and measuring a few millimeters (mm) in size. The conventional method for determining location is to use GPS. However, the received signal from the satellites is very weak (-155 dBm) and hence requires a power-hungry, very low noise amplifier (e.g., 25 mW by Mediatek MT3339). To power such a system requires, at minimum, a coin cell-sized battery, which by itself already weighs ~200 mg. Furthermore, the GPS carrier frequency of 1.58 GHz requires a relatively large, centimeter (cm) scale antenna. As a result, the smallest commercial GPS system (PinPoint by Lotek Wireless) has a total weight of 1.1 g and size of 5 cm [2]. An alternative to GPS is the Motus system [3], which uses a radio beacon with tens of km transmission distance attached to each specimen combined with geographically distributed receiving towers. However, while receiving towers are relatively dense in Ontario and along the eastern seaboard, there are very few along the primary monarch migration region in the Midwest. Also, they require a long antenna (multiple cm) and have a weight >230 mg, which likely significantly impedes monarch flight [4]. Finally, daylight trackers were proposed to compute location based on sunrise/set times (e.g., Intigeo by Migrate Technology [5]). However, their data readout requires physical access to the sensor, which is impractical in the case of monarch migration. Furthermore, their size/weight (320 mg and 12 × 5 × 4 mm) remain well beyond that required for the monarch and, with only daylight-based sensing, location accuracy is limited, especially during the equinox.

PROPOSED WIRELESS SENSING PLATFORM: mSAIL

We propose a new wireless sensing platform, *mSAIL* (Figure 1) specifically designed for the monarch migration study based on previously developed custom-designed integrated circuits (IC) [6] – [11]. mSAIL is an energy harvesting, 62 mg device with a 8 × 8 × 2.6 mm form-factor (including antenna), that 1) simultaneously measures light intensity [6] and temperature [7] using non-uniform temporal sampling; 2) compresses the recorded data in 16 kB memory; 3) wirelessly communicates data up to 150 m distance using a crystal-less radio at the overwintering site in a realistic non-line of sight (NLOS) scenario to custom-designed gateways; and 4) achieves energy autonomy by continuously recharging an integrated, chip-size battery, using a custom-designed light-harvesting IC with eight photovoltaic (PV) cells. mSAIL addresses the following major technical challenges:

- **Millimeter & milligram form factor:** mSAIL must be small and light in order to not interfere with monarch flight and accurately record migration paths. A monarch weighs approximately 500 mg, and its thorax is approximately 3 mm wide. Therefore, in order for the wings to properly close, a tagging unit must be <3 mm wide and, to avoid restricting movement, it must be no more than 8 mm long. For vertebrate animals, weight for animal bio-loggers is typically <5% body weight [12]. However, insects can carry significantly more weight [4] and our preliminary respiratory study indicates even <15% is still acceptable (75 mg), although weight should always be minimized to the greatest extent possible. mSAIL meets these stringent specifications through multiple techniques: instead of one large chip, we stack small dies of previously designed ICs to obtain a compact design [8], [13] as shown in Figure 1; we thin each die to 100 μm thickness to reduce stack height; we use a custom designed chip-scale rechargeable battery that integrates in the same chip stack; we use a ultra-low-power (ULP) radio removing the need for an RF-reference (typically >10 MHz) crystal [9]; finally, our transmitter/antenna co-design enables a 8 × 8 mm antenna while achieving >150 m distance.

- **Energy autonomy:** The highly constrained form factor limits available battery size and thus its capacity to only 18 μAhr. Within

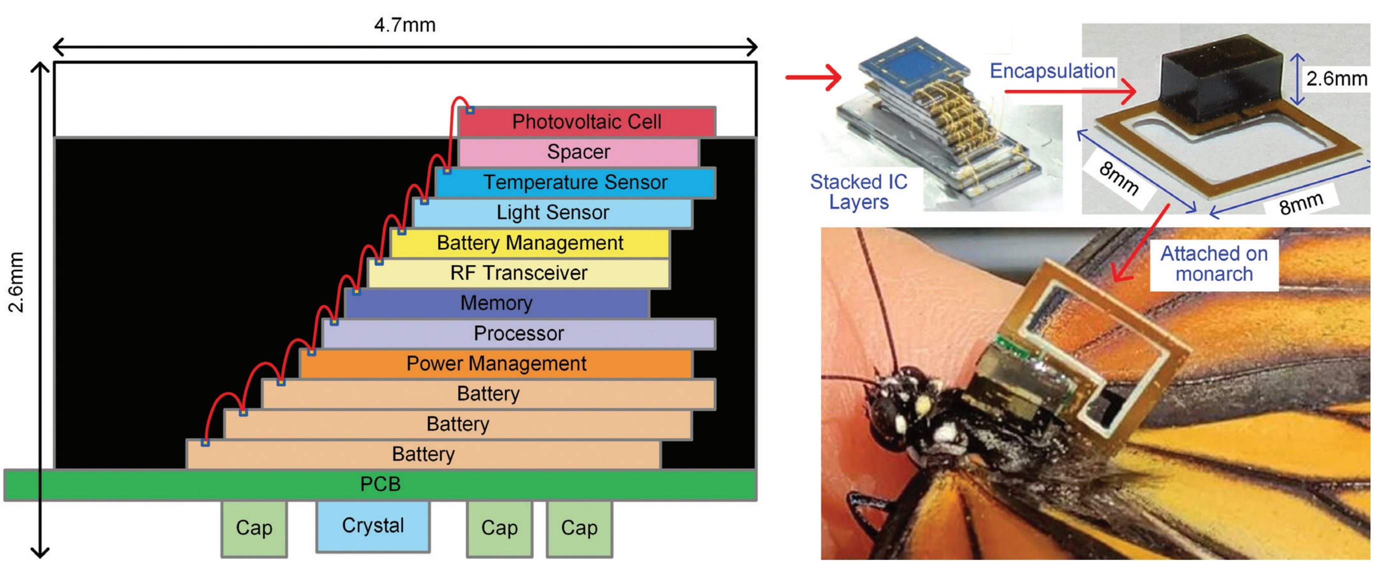

FIGURE 1. Proposed embedded system, mSAIL.

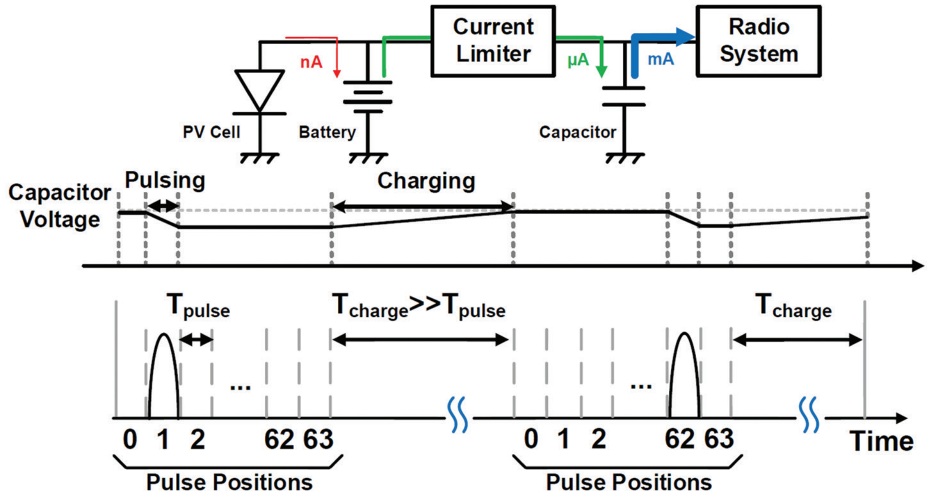

FIGURE 2. Modulation and recharging scheme of a custom sparse pulse position modulation transceiver IC for wireless communication.

this very limited energy budget, the tracking device must periodically record sensor data for 3 months and radio out the data at the end. mSAIL minimizes energy by employing three different operation modes: sleep (218 nW), active sensing (86 μW) and wireless communication (130 μW), each with mode-specific power management. Sleep uses ULP data retention memory, light sensing, and always-on 32 kHz real-time crystal oscillator. By maximizing sleep time (99.3%), average current draw is reduced to 201 nA at a battery voltage of 3.9 V. The custom GaAs PV IC [10] is able to maintain battery charge at 5 klux and the battery capacity is sufficient to radio out all the data at the overwintering site.

• **Limited data storage:** mSAIL uses custom ultra-low-leakage (ULL) SRAM for static power reduction [11]. However, the limited silicon area allows only 16 kB memory space for data storage. To minimize the required memory space for the 3-month migration data, we compress light, temperature and time-stamp data using a dynamic sampling interval scheme, which has finer data resolution around the sunrise/set that most accurately predicts monarch location. A combination of the data compression and dynamic sampling interval reduces the required memory space from 772 kB to 7.2 kB, making 3-month tracking feasible.

• **Wireless communication:** Since monarchs overwinter in dense clusters, often high up in trees, long distance (>100 m) wireless communication is essential. However, mSAIL imposes extreme constraints on antenna size (8 × 8 mm) resulting in low antenna efficiency of -8 dBi. In addition, the mm-scale battery can sustain a maximum current draw of only 60 μA due to its high internal resistance. We address this challenge by using a custom sparse pulse position modulation transceiver IC, which accumulates charge on a capacitor between pulses, enabling 3.3 dBm transmit power, as shown in Figure 2 [9]. However, the transceiver IC exhibits high carrier frequency uncertainty and offset because it operates without a RF-reference crystal (typically >MHz), nor a PLL, to reduce the system size, weight, and power. This makes narrowband wireless communications more challenging. We address this using a new 2D-FFT based carrier and sampling-frequency offset joint estimation algorithm on an Ettus Research USRP X310 compatible, custom gateway for real-time RF communication.

MONARCH MIGRATION TRACKING APPLICATION SCENARIO

mSAIL records light intensity and temperature with accurate, 32 kHz crystal-based time-stamps along the monarch migration path. Standard light-based locationing determines the sunrise and sunset time using a light intensity threshold and then determines the geolocation. The day length and center time depend on the geolocation and date, and have been used in long-term larger animal tracking studies. However, it has the fundamental limitation of large latitude ambiguity around the equinox (September 22 and March 20) when the day length is the same regardless of latitude. A second challenge is the significant light intensity variation due to weather and terrain that an ideal sunlight intensity model is unable to capture.

mSAIL adopts a novel data-driven algorithm for monarch migration tracking that leverages the principle of correlating multiple sensors. It achieves superior accuracy by applying deep neural network (DNN) models and multimodal fusion to effectively combine multiple sensor readings, including light intensity and temperature. The objective of the DNN approach is to identify cross-correlation between the multimodal readings and the sunlight intensity pattern as well as temperature information on a particular date. Different from handcrafted models for light intensity and temperature, the DNN approach learns an implicit, yet more complicated model from real sensor measurements, which makes it more robust to local variations.

Although the details of the trajectory are not known, the final destination of the monarch migration is known. Overwintering monarchs will distribute over a limited number of sites within central Mexico with 21-78% of the total population reliably congregating at a single site (El Rosario sanctuary of the Monarch Butterfly Biosphere Reserve) each year. mSAIL nodes will be programmed with a predefined rendezvous time to start wireless data offloading to multiple gateways deployed at that over-wintering site. This scenario allows retrieval from both fallen (dead) and live monarchs as long as they are within the communication range. Since an estimated ~90% of monarchs survive at the overwintering site, the data recovery rate is expected to be significantly improved compared with current paper tagging methods [14] that can primarily access dead butterflies. After a gateway retrieves the data log from an mSAIL, the entire butterfly trajectory can be constructed using the DNN localization algorithm proposed in [15], as shown in Figure 3(a). The DNN is trained and evaluated by the data collected through a data measurement campaign with 306 volunteers from 2018–2020 across the US, Canada, and Mexico. They recorded light intensity and temperature using commercial cm-scale sensors (ONSET MX2202) as an emulator of mSAIL during the monarch migration season. The localization algorithm

[15] shows a geocoordinate accuracy of <0.6° and <1.7° in longitude and latitude respectively (1° is ~85.2 km in longitude and ~111.2 km in latitude in the midwestern US), which is sufficient for monarch studies.

LIVE MONARCH LOCALIZATION

Full system operation of mSAIL was demonstrated attached to a live monarch butterfly in a botanical garden, as shown in Figure 4. The butterfly is kept in an outdoor, 42 × 42 × 76 cm cage, positioned on a 2.5 m tall pergola such that the cage is not shaded by nearby buildings, on November 6th and 7th, 2020, which is during the monarch migration season. For reference measurements, cm-scale sensors were placed in the cage and outside on the pergola. A receiving gateway with a 7" omnidirectional whip antenna was mounted 8 m away in a nearby enclosed structure to receive the transmitted data regardless of weather conditions.

We evaluate our 2-day measurements in a grid surrounding the ground-truth location with a range of [-15, 15] degree in latitude and longitude and a resolution of 0.25 degree. The likelihood (i.e., DNN outputs) for the grid points are visualized as heatmaps shown in Figure 3(b), where the center of the graph is the ground-truth location. It is observed that light intensity alone is able to provide accurate longitude estimation and that temperature significantly refines the latitude estimation. The maximum likelihood estimations marked in the figure provide an absolute error of 0.07°/0.26° in longitude and 0.03°/0.40° in latitude for the first/second day, which translates to a maximum error of 21.4 km and 44.5 km in longitude and latitude and aligns with the accuracy reported in [15] evaluated with the cm-scale sensors.

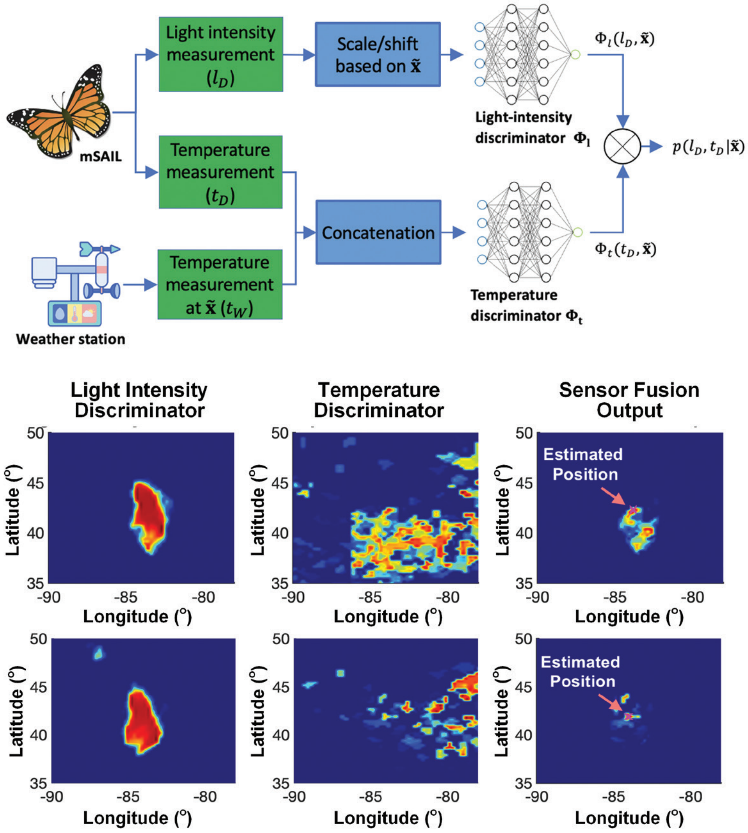

FIGURE 3. DNN localization. (a) Algorithm using mSAIL light and temperature measurement data; (b) Localization likelihood output for two different days (top) and (bottom). Center of each heatmap is the ground-truth. Maximum error after sensor fusion is 21.4 km and 44.5 km in longitude and latitude.

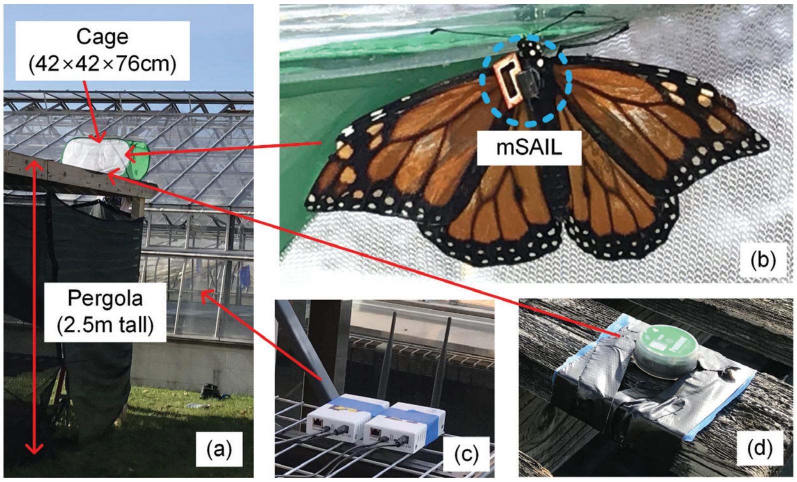

FIGURE 4. Testing setup for the outdoor botanical garden test. (a) Overview; (b) mSAIL on monarch; (c) Gateway; (d) Centimeter-scale commercial sensor.

CONCLUSION AND FUTURE PLAN

mSAIL, for the first time, demonstrates the feasibility of individual butterfly localization and tracking using a novel 8 ×8 ×2.6 mm and 62 mg embedded system that integrates custom-fabricated solar energy harvester, ultra-low power processor, light/temperature sensors, and wireless transceiver ICs, all within a 3D stacked form-factor.

Our long-term goal is to estimate and reconstruct the entire migration path of monarch butterflies in the wild using mSAIL. We are currently working on mass (> 100 units) production of mSAIL sensors that reliably operate during the 3-month monarch migration period. mSAIL instrumented butterflies will be released in various locations in the U.S. and wireless data retrieval will be conducted at known resting locations, such as islands in the western Lake Erie archipelago, and at the final overwintering site in central Mexico. In the future, for higher localization accuracy, we plan to add an air pressure sensor to mSAIL providing altitude information for an enhanced localization algorithm. ■

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